

Effects of pre-corrosion, water and detergent contamination on rolling contact fatigue

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Abstract. The effects of pre-corrosion, water and detergent contamination in Shell Turbo 32 (T32) mineral oil on rolling contact fatigue (RCF) life of rollers were experimentally investigated using a home-made ball-on-roller tester. The tested roller samples were analyzed by a scanning electron microscope (SEM) and an energy dispersive spectrum (EDS). The results show that the fatigue life of the rollers is reduced by all test conditions where the negative effect is enhanced with increasing the pre-corrosion time, from surfactant detergent to water contamination and to alkaline detergent. Microscopic analysis indicates that spalls on the rolling contact track are mainly surface initiated.

Keywords: Rolling contact / fatigue / additives / corrosive

1 Introduction

Water contamination in lubricants is among the top causes of rolling element bearing failure in many applications [1–4]. Grunberg and Scott [5] demonstrated using a 4-ball tester that lubricant oil with saturated water reduced the rolling contact fatigue life significantly. Microscopic analysis showed that the failure mode was spalling initiated from surface cracks. Schatzberg and Felsen [6,7] conducted similar studies using a 4-ball tester but with angle contact under 8.96 GPa contact pressure and found that the rolling contact fatigue life was reduced by 32 to 48% when the lubricating oil contained water even the content was as low as 0.01%. They hypothesized that water may penetrate through surface cracks to the steel substrate which results in hydrogen embrittlement and electrical chemical reaction enhancing the crack initiation and propagation. Similar results were obtained by Cantley [1]. Felsen et al. [8] tested the effect of sea water contamination on the fatigue life of angle contact ball bearings and the results showed significant reduction on the fatigue life. They found out that sea water was in emulsion state in the oil and postulated that the impregnation of water in the cracks would accelerate the

fatigue failure. Grunberg et al. [9] identified the presence of hydrogen in the cracks and concluded that hydrogen was decomposed from water. Kino and Otani [10] confirmed the effect of hydrogen embrittlement on the premature failure of bearings in a power transmission system of automobiles.

In some application environment, there exists detergents which may also enhance the negative effect of water contamination. Detergents usually consist of surfactants and other chemicals such as alkaline and acid, and are often used for cleaning purposes during which detergents may enter into bearing and contaminate the lubricants. The effect of water contamination on bearing fatigue life may attribute to two major mechanisms: corrosion (corrosion pits and hydrogen embrittlement) and break-down of lubricant film in the rolling contact surfaces. There is no clear evidence to confirm which mechanism plays the major role in a specific condition. There is also limited research on the effect of detergent contamination on the rolling contact fatigue life.

In this paper, a home-made ball-on-roller rolling contact fatigue (RCF) tester [11] is used to evaluate the effects of water and detergent contamination. In addition, pre-corroded rollers are also tested to identify which mechanism (corrosion or film breakdown) may play the major role. Detailed microscopic analysis is conducted to identify whether the damage initiates from surface or sub-surface. The plausible damage mechanism is discussed.

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2 Experimental methods

2.1 The ball-on-roller tester

The home-made ball-on-roller rolling contact fatigue (RCF) tester is modified from a driller (Z4120, supplied by Hangzhou Shuanglong Machinery Co., Ltd.), as shown in Figures 1 and 2. Three bearing steel balls with a diameter of 20 mm are loaded on a bearing steel roller with a diameter of 18 mm and length of 26 mm forming point contacts. The three balls are evenly spaced and loaded by two cone rings which are from two tapered roller bearings (31305), as shown in Figure 3.

The roller is driven by the transmission rod of the driller. Vertical slots are made on the upper and lower end faces of the roller to ensure the alignment of the transmission rod and the roller. The slot of the lower end of the roller is connected to the support shaft, which sits on a spring. The three steel balls are driven by the driller to form planetary motion around the roller in the raceway of two rings. The lower support shaft, which tightens the roller through the spring force, rotates with the roller. The applied load on the upper cone ring is realized by the weight.

The external force P is transmitted to the cone ring through the loading sleeve, as shown in Figure 3. The forces at the ball-cone ring contact and ball-roller contact are R and Q , respectively.

For the ball-cone ring contact:

$$3R \sin \theta = P \quad (1)$$

For the ball-roller contact:

$$2R \cos \theta = Q \quad (2)$$

therefore:

$$Q = \frac{2P}{3 \tan \theta} \quad (3)$$

A LabVIEW-based measurement-and-control system was developed to monitor the vibration and temperature of the test rig in real time, collect time and frequency domain signals during vibration, and monitor the wear state of the roller. The vibration is detected by an accelerometer. When the vibration is higher than a pre-defined limit, indicating the formation of a fatigue spall, the test will stop and the measurement data will be stored automatically.

2.2 Lubricant oil and contamination

The lubricant oil and contamination are listed in Table 1. A mineral oil Turbo 32 (T32) from Shell, which is without anti-wear and extreme additives, is used. For water contamination test, 5 wt.% of demineralized water is added by mechanical stirring. Two types of detergent contamination are adopted. Detergent A consists of 99 wt.% demineralized water and 1 wt.% alkylamineoxides which is a surfactant and neutral in pH.

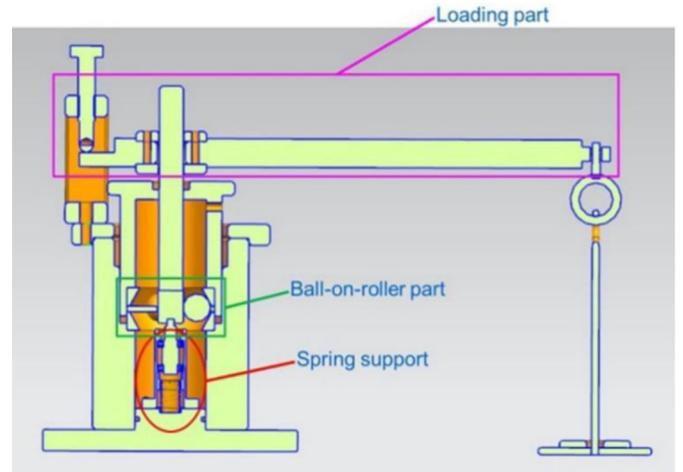


Fig. 1. Setup drawing of RCF test rig.

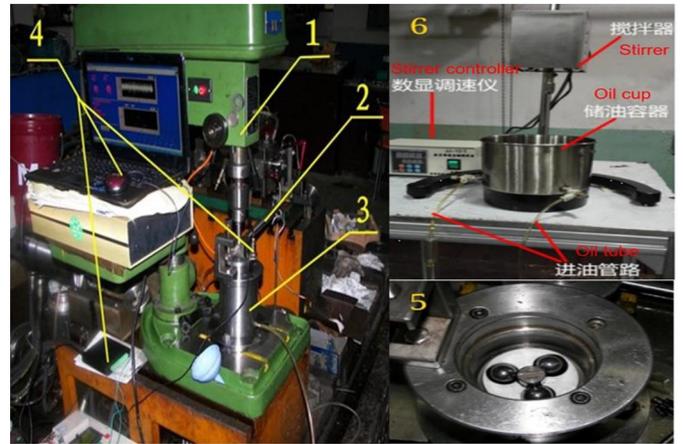


Fig. 2. Test rig. (1) Driller; (2) loading part; (3) mechanical part of test; (4) vibration measurement and controller; (5) inside of part 3; (6) lubrication part.

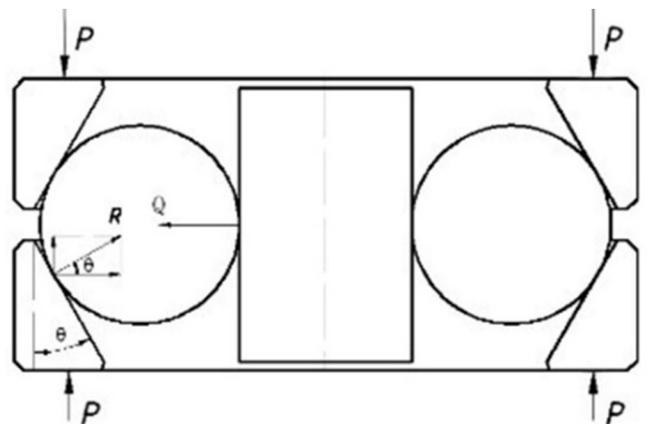


Fig. 3. Force analysis at the contact point between roller and ball.

Detergent B consists of 95 wt.% demineralized water and 5% mixture of aqueous solution of 1–5% of alkylamineoxides, 2–5% of NaOH and 2.5–5% of NaClO, which is strong alkaline (pH 13 to 14).

Table 1. Lubricant and contamination.

Oil or contamination	Description
1. Lubricant oil	Shell Turbo 32 (T32): Pure oil without extreme pressure and anti-wear additives ISO viscosity: 32 cSt at 40 °C and 5.2 cSt at 100 °C
2. Water contamination	Demineralized water
3. Detergent A	99 wt.% demineralized water + 1 wt.% alkylamineoxides; pH ~7.
4. Detergent B	95 wt.% demineralized water + 5 wt.% of aqueous solution of (1–5% alkylamineoxides, 2–5% NaOH, and 2.5–5% NaClO); pH 13 to 14.

Table 2. Test conditions.

Ball and roller material		Martensitic Steel ANSI 52100	
Roller diameter	18 mm	Applied load	35 kN
Roller length	26 mm	Maximum Hertz contact stress	5.3 GPa
Roller hardness	62 HRC	Roller rotating speed	4100 rpm
Roller surface roughness Ra	0.08 μm	Lubricant	Shell Turbo 32, mineral oil
Ball diameter	20 mm	Lubrication method	Circulation, stirring in the oil bath
Ball hardness	58–62 HRC	Oil temperature	48 \pm 1 °C (outer ring)
Ball surface roughness Ra	0.02 μm	Lubricant film thickness	0.209 μm
Lubrication parameter	$\lambda = 3$, $\kappa \sim 2.5$ (EHL full film)	Maximum testing period	200 h

2.3 Test conditions

The test parameters are listed in Table 2. The specimen rollers and balls were supplied by SKF and Shanghai Steel Ball Factory. In the contact between the roller and balls, there is no gloss slip. The tester is lubricated by an oil circulating system. An agitator is used to stir the lubricating oil in the oil storage container to allow sufficient mixture of water with oil and avoid separation of water and oil.

The Hertz contact pressure is calculated to be 5.3 GPa, which is very high and is higher than the shaken down stress limit of the hardened bearing steels. The purpose of selecting such a high value is to accelerate the test.

The rollers without pre-corrosion are dripped in the 0.5% NaCl aqueous solution, and the pre-corroded rollers are dipped into oil bath at 40 °C for 2 different standstill times (6 h and 24 h) for pre-corrosion in anaerobic environments. Rollers with pre-corroded stripes are shown in Figure 4. The pre-corroded rollers were then tested for RCF performance by using the pure T32 oil under the conditions described in Table 2.

3 Experimental results and discussion

3.1 Effect of pre-corrosion on RCF life

Five tests were conducted with new rollers and four tests were conducted with the pre-corroded rollers. The test results are summarized in Table 3 and analyzed by using Weibull program and plotted in Figure 5. The results show that the pre-corrosion reduces the RCF life

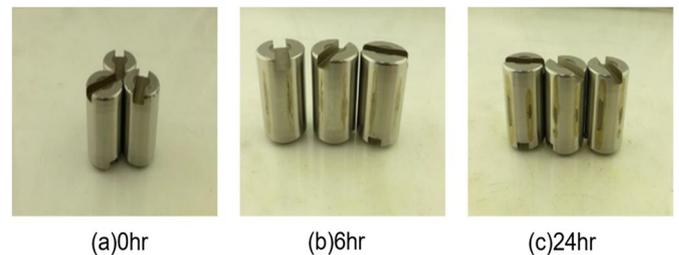


Fig. 4. (a) Roller without pre-corrosion. (b) Pre-corroded rollers after 6 h standstill. (c) Pre-corroded rollers after 24 h standstill.

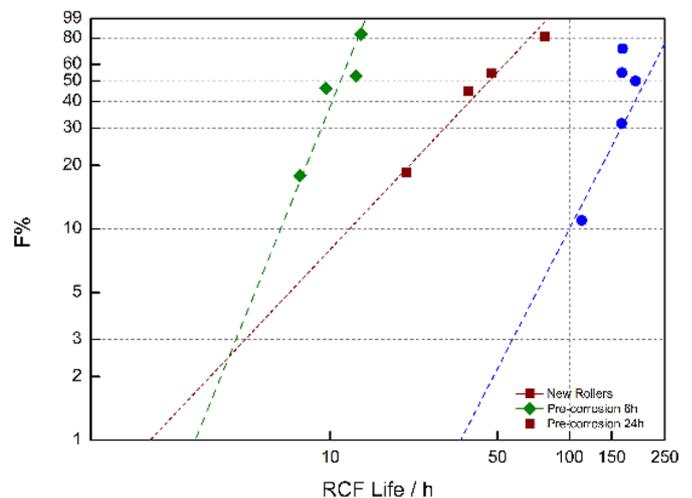
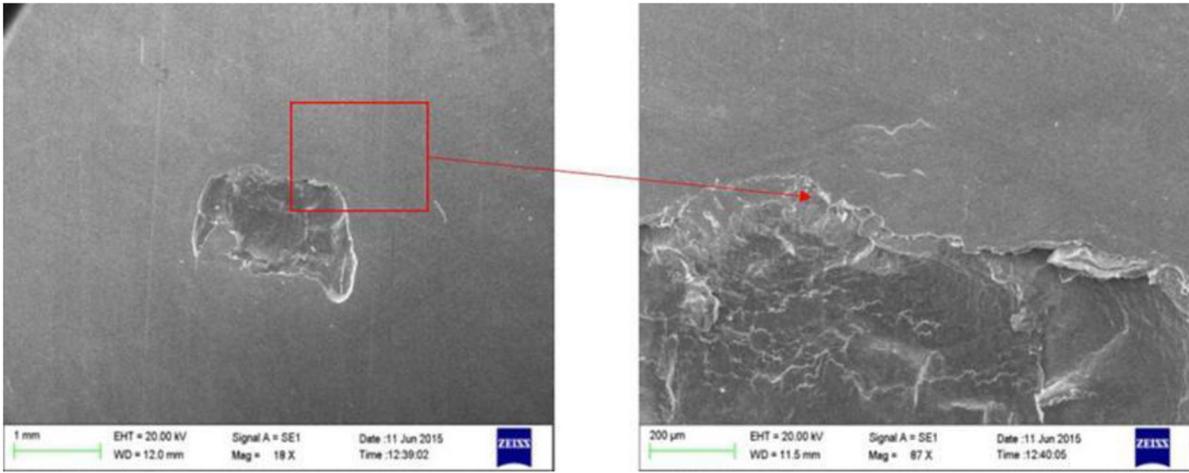
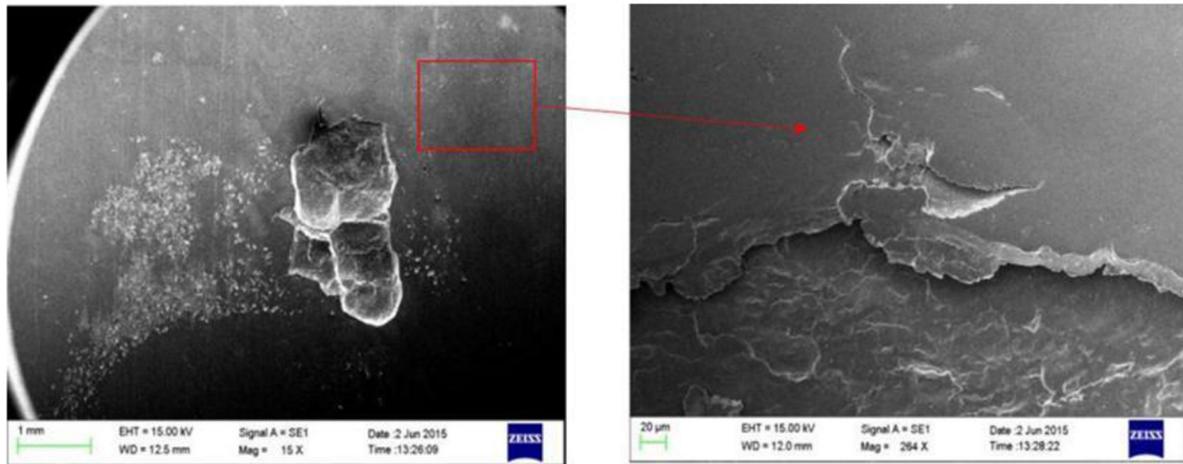


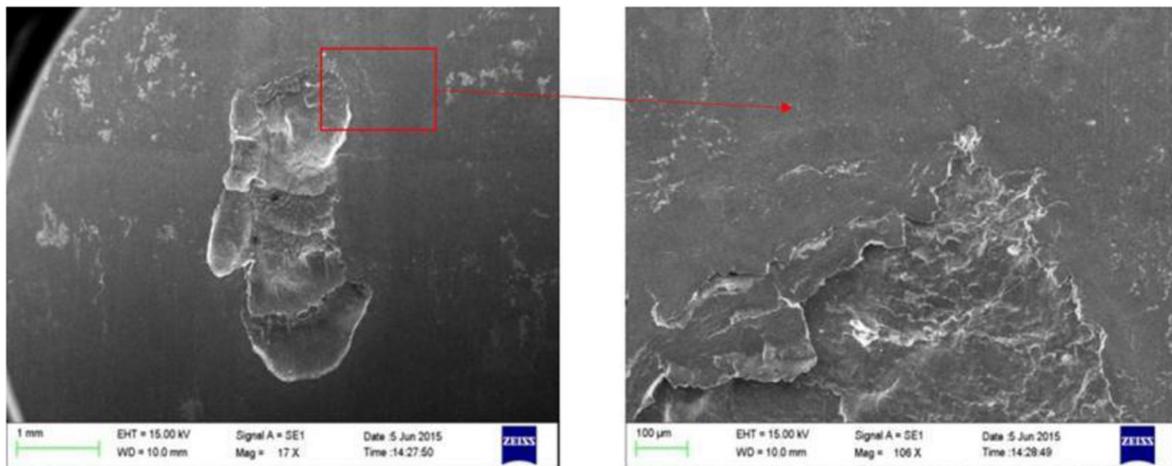
Fig. 5. Weibull plot of the RCF life of rollers with two pre-corrosion times.



New rollers



Pre-corroded rollers 6 hr

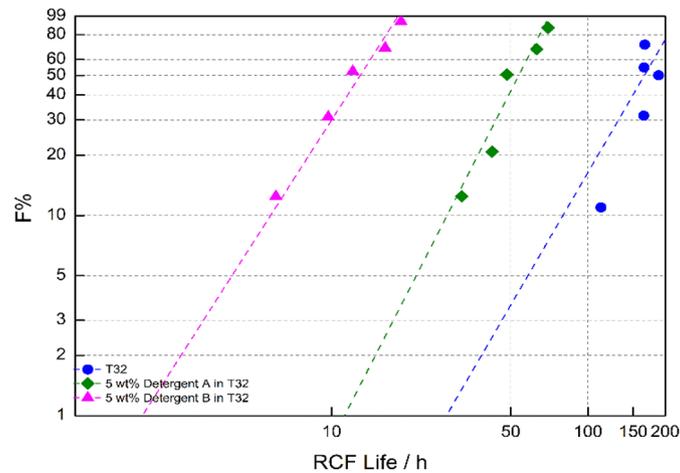
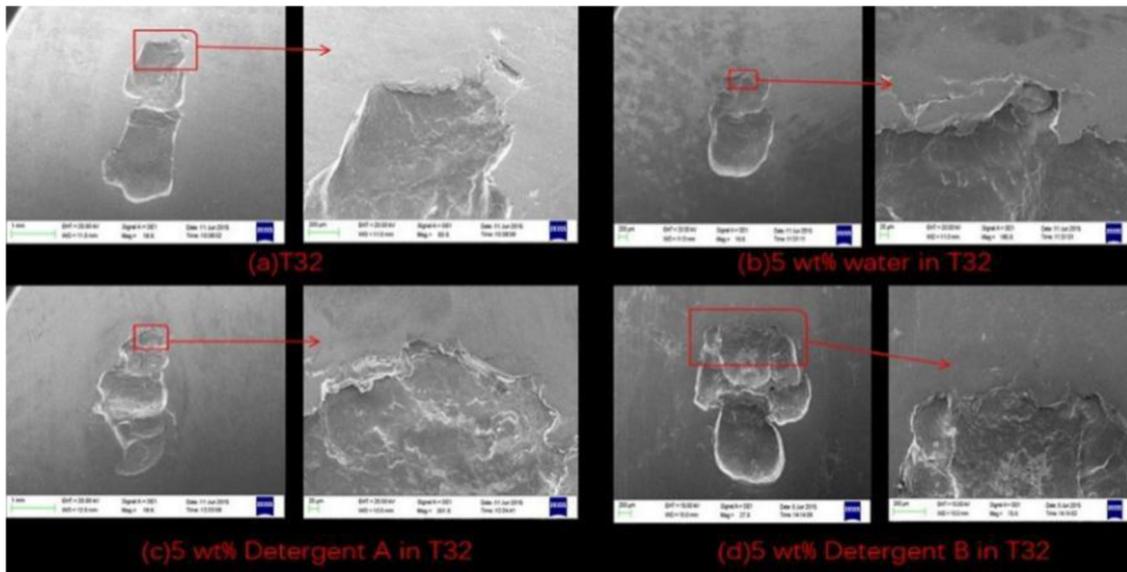


Pre-corroded rollers 24 hr

Fig. 6. SEM images of RCF spalling of rollers with different pro-corrosion severity. (Over-rolling direction is downwards).

Table 3. Test results of pre-corroded rollers.

Lubricating oil	Roller	Time to failure(h)					L10 life (h)	β -slope
		#1	#2	#3	#4	#5		
T32	New rollers	197.0	83.5	100.0	122.3	107.6	136.3	3.19
T32	Pre-corroded rollers 6 h	64.3	33.0	16.0	13.6	–	9.40	1.69
T32	Pre-corroded rollers 24 h	23.8	8.5	9.1	22.4	–	7.3	2.48

**Fig. 7.** Weibull plot of the RCF life in different oil-detergent mixtures.**Fig. 8.** SEM images of RCF spalling in different oil-detergent mixtures. (Over-rolling direction is downwards).

significantly and the longer pre-corrosion time (24 h) can reduce the life further. The β -slopes of pre-corroded rollers are larger than 1.6, indicating a cumulative failure mechanism rather than a random premature failure [12].

The failed rollers were investigated by using scanning electron microscope (SEM) and the results are shown in Figure 6. Large spalling is the typical failure mode.

According to the morphology of the spalls, the spalls on the new rollers are sub-surface initiation and those on the pre-corroded rollers are mostly surface initiation. Corrosion pits were observed on the initiation sites of the spalls, indicating that the spalls were initiated from the corrosion pits. The initiation sites of spalls are however not located on the pre-corrosion contact positions for all the rollers.

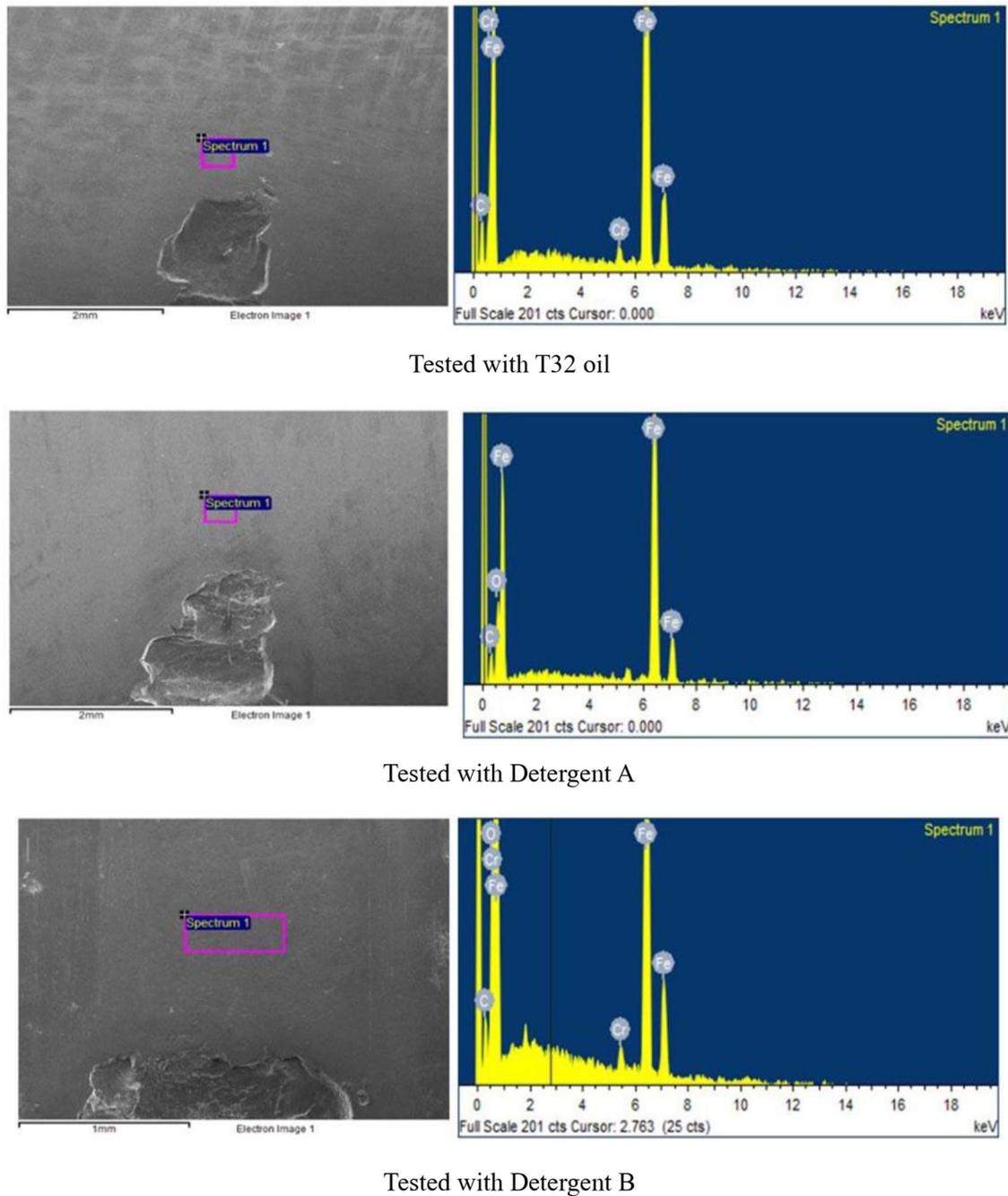


Fig. 9. EDS composition analysis on the rollers surface in front of spalls.

3.2 Effect of detergents contamination on RCF life

Five tests were conducted for each condition (water and detergent contamination) with the home-made ball-on-roller tester. The test results are summarized in Table 4 and are analyzed by using Weibull program and plotted in Figure 7. The results show that water contamination and detergent contamination in lubricating oil reduces the RCF life significantly: the effect of the alkaline detergent B has the strongest negative effect, followed by the water contamination and the surfactant

detergent A. The β -slopes for the detergent B is relatively higher (2.4–4.6), which may indicate the existence of some dominating parameters on the failure mechanism [12].

Large spalls were observed by SEM and are the roller failure mode as shown in Figure 8. The spalls on the rollers tested from the water and detergent contamination are mostly surface initiation as shown in Figure 8. High oxygen content was observed by an Energy Dispersive Spectrum (EDS) analysis in front of the spalls of rollers from detergent contaminated tests, as shown in Figure 9.

Table 4. Test results of water and detergent contamination.

Lubricating oil	Roller	Time to failure(h)					L10 life (h)	β -slope
		#1	#2	#3	#4	#5		
T 32	New	197.0	83.5	100.0	122.3	107.6	136.3	3.19
5 wt.% water in T32	New	31.2	41.2	21.5	18.8	15.3	13.4	2.95
5 wt.% Detergent A in T32	New	82.4	94.0	37.5	30.2	42.3	25.8	2.44
5 wt.% Detergent B in T32	New	16.0	10.0	8.2	11.0	14.9	8.09	4.59

This observation indicates that corrosion occurred prior to spalling.

There is a clear evidence that the spalls on the pre-corroded rollers were initiated from corrosion pits. This result confirmed that stand-still corrosion can reduce the rolling contact fatigue life significantly.

Usually water and oil are not well mixed. Detergent A consists of surfactant and may be emulsified in the oil forming small water droplets. Detergent B consists of both surfactant and alkaline chemicals in which the alkaline chemicals may react with oil and change the lubricating properties of the oil. Therefore, the alkaline Detergent B has a stronger negative effect on rolling contact fatigue life than water and Detergent A. It seems that both corrosion and lubricating film break-down play important role on reducing the rolling contact fatigue life when there is water or detergent contamination in lubricating oils.

4 Conclusions

Pre-corrosion, water contamination and detergent contamination in lubricant oil can reduce RCF life significantly. It seems that alkaline detergent may enhance the negative effect. The failure modes are surface initiated spalls. Detailed failure mechanism needs to be further explored.

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